# The Shifted Peak: Resolving Nearly Degenerate Particles at the LHC

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We propose a method for determining the mass difference between two particles, $\tilde{l}_1$ and $\tilde{l}_2$, that are nearly degenerate, with $\Delta m \equiv m_2 - m_1 \ll m_1$. This method applies when (a) the $\tilde{l}_1$ momentum can be measured, (b) $\tilde{l}_2$ can only decay to $\tilde{l}_1$, and (c) $\tilde{l}_1$ and $\tilde{l}_2$ can be produced in the decays of a common mother particle. For small $\Delta m$, $\tilde{l}_2$ cannot be reconstructed directly, because its decay products are too soft to be detected. Despite this, we show that the existence of $\tilde{l}_2$ can be established by observing the shift in the mother particle invariant-mass peak, when reconstructed from decays to $\tilde{l}_2$. We show that measuring this shift would allow us to extract $\Delta m$. As an example, we study supersymmetric gauge-gravity hybrid models in which $\tilde{l}_1$ is a meta-stable charged slepton next-to-lightest supersymmetric particle and $\tilde{l}_2$ is the next-to-lightest slepton with $\Delta m \sim 5$ GeV.

**Introduction.** How well can we measure the masses of new particles at the LHC? This question might seem secondary at the early stages of discovery. It becomes significant, however, if there are two new particles that are nearly degenerate, with a mass difference of the order of a few GeV. In the busy LHC environment, it will be highly non-trivial to observe such mass differences. On the other hand, it is quite natural to expect such scenarios. If the new physics replicates the three-generation structure of the standard model, then we could easily have particles with the same gauge charges whose mass differences only depend on small "flavor effects." Obvious examples are the squarks and sleptons of supersymmetry, particularly the first- and second-generation ones. Here we propose an indirect method for resolving such mass differences, which applies when (a) the momentum of the lighter particle can be measured, (b) the heavier particle can only decay to the lighter particle, and (c) the two particles can be produced in the decays of a common mother particle. For concreteness, we will discuss the case of two sleptons, $\tilde{l}_{1,2}$, with $\Delta m \equiv m_2 - m_1 \ll m_1$, with a meta-stable $\tilde{l}_1$. Such a spectrum is predicted by supersymmetric models [1, 2, 3] that explain the masses and mixings of the standard model charged leptons and neutrinos in terms of broken flavor symmetries [4]. More generally, this scenario is often realized in gauge-mediated supersymmetry breaking models [5], and in large regions of the parameter space of models with gravity-mediated supersymmetry breaking [6]. Since the meta-stable $\tilde{l}_1$ leaves a track in the muon detector, its momentum can be measured, and the event is fully reconstructible. Similar spectra and phenomena are also possible in other frameworks, such as for the Kaluza-Klein excitations of quarks and leptons in models with universal extra dimensions [7].

The method relies on the decays of a mother particle, in this case the neutralino $\chi_1^0$, to $\tilde{l}_{1,2}$. If we use direct decays to $\tilde{l}_1$ to reconstruct the neutralino, the invariant mass distribution will be peaked at the correct neutralino mass. Some of the time, however, the neutralino decays to $\tilde{l}_2$, which subsequently decays to $\tilde{l}_1$. The leptons produced in the $\tilde{l}_2 \to \tilde{l}_1$ decay are relatively soft, with energies typically of the order of $\Delta m$. They may therefore be lost, implying that the decays $\chi_1^0 \to \tilde{l}_1$ and $\chi_1^0 \to \tilde{l}_2$ have the same topology. Rather than blurring the picture, however, we show that by attempting to reconstruct the $\chi_1^0$ in both cases, one can in fact find two peaks: one at the neutralino mass $M$, and one slightly shifted to a lower value by an amount $E_{\rm shift} \sim \Delta m$. Thus, measuring a shift in the neutralino mass peak will tell us that there are in fact two slepton states lighter than the neutralino, with a mass difference roughly given by $E_{\rm shift}$. Furthermore, if the two particles in question are scalars (which can be established from the angular distribution of the decays), $\Delta m$ can be determined in terms of $E_{\rm shift}$, $m_1$, and the neutralino mass $M$.

**The Shifted Peak.** By assumption, the neutralino has two possible decays into sleptons. The first is the direct decay to $\tilde{l}_1$,

$$\chi_1^0 \to \tilde{l}_1^{\pm} l_1^{\mp} \ . \tag{1}$$

The second is the decay to $\tilde{l}_2$,

$$\chi_1^0 \to \tilde{l}_2^{\pm} l_2^{\mp} \ , \tag{2}$$

followed by one of the two three-body decays [8, 9]

$$\tilde{l}_2^{\pm} \to \tilde{l}_1^{\pm} X^{\pm\mp} \ , \tag{3}$$

$$\tilde{l}_2^{\pm} \to \tilde{l}_1^{\mp} X^{\pm\pm} \ , \tag{4}$$

where $X^{\pm\mp}$ contains two opposite-sign (OS) leptons, and $X^{\pm\pm}$ contains two same-sign (SS) leptons. Note that

the charge-flipping decays of Eq. (4) resulting in SS leptons are possible because the neutralino is a Majorana fermion; SS leptons are also present in models other than supersymmetry when the decay is mediated by a vector boson or a scalar. We denote these lepton pairs by $X$ to emphasize the fact that they are too soft to pass our cuts. Thus, the observed particles are the hard lepton from Eq. (1) or (2), and the long-lived slepton $\tilde{l}_1$ from Eq. (1), (3), or (4).

We can thus construct distributions for the following invariant masses-squared:

$$\begin{aligned} m^2_{\tilde{l}l_1} &\equiv \left(p_{\tilde{l}_1} + p_{l_1}\right)^2 \ , \\ m^2_{\tilde{l}l_2} &\equiv \left(p_{\tilde{l}_1} + p_{l_2}\right)^2 \ , \end{aligned} \tag{5}$$

where the $\tilde{l}_1$ and $l_2$ charges can be either opposite or the same. Obviously,

$$m_{\tilde{l}l_1} = M \ , \tag{6}$$

where $M$ is the neutralino mass. However, because of the missing soft leptons,

$$m_{\tilde{l}l_2} \neq M \ , \tag{7}$$

and the peak of the $m_{\tilde{l}l_2}$ distribution is shifted from $M$ to $M - E_{\text{shift}}$.

The identities of $l_1$ and $l_2$ depend, of course, on the flavor decompositions of $\tilde{l}_1$ and $\tilde{l}_2$, respectively. In one extreme case, if $\tilde{l}_{1,2}$ are the left- and right-handed sleptons associated with the same flavor, the two leptons are identical. Still, a peak in the invariant mass $m^2_{\tilde{l}_1^\pm l_2^\pm}$, formed from events with SS sleptons and leptons, can only come from the decays of Eq. (2) and will therefore exhibit the shift $E_{\text{shift}}$. The analogous OS distribution will contain both types of events specified in Eqs. (1) and (2), and so will exhibit a double peak structure, with the two peaks separated by $E_{\text{shift}}$.

In the opposite extreme, the two sleptons could be pure states of different flavors. In this case, the leptons $l_1$ and $l_2$ are different flavors, and there is no need to rely on the charges to separate the distributions. In any case, we can use the shifted peak to infer the existence of two distinct states. In the following, for the sake of simplicity, we will consider the second case, and take $\tilde{l}_1 = \tilde{e}$ and $\tilde{l}_2 = \tilde{\mu}$ so that $l_1 = e$ and $l_2 = \mu$.

We now turn to the calculation of the peak shift $E_{\text{shift}}$. We denote the four momentum of a particle $a$ by $p_a$, and the $\tilde{l}_1$ energy by $E_1$. Then,

$$m^2_{\tilde{l}\mu} = M^2 - m_2^2 + m_1^2 - 2 p_\mu \cdot p_X \ . \tag{8}$$

From here on, we neglect the lepton masses. Working in the $\tilde{l}_2$ rest frame, we take the $x - y$ plane to be the plane of the muon and dilepton momenta, $\vec{p}_\mu$ and $\vec{p}_X$. We further take the muon direction to define the $\hat{x}$-axis. The four-momenta of the hard muon and of the soft dilepton are then given by

$$p_\mu = \frac{M^2 - m_2^2}{2m_2}(1, \hat{x}) \ , \tag{9}$$

$$p_X = \left( m_2 - E_1, -\hat{n}\sqrt{{E_1}^2 - m_1^2} \right) \ , \tag{10}$$

where $\hat{n} = (\cos\theta, \sin\theta, 0)$. Substituting Eqs. (9) and (10) into Eq. (8), we find

$$m^2_{\tilde{l}\mu} = m_1^2 + \frac{M^2 - m_2^2}{m_2} \left( E_1 - \cos\theta \sqrt{E_1^2 - m_1^2} \right), \tag{11}$$

with $E_1$ and $\cos\theta$ varying *independently* in the intervals

$$E_1 \in \left[ m_1, \frac{m_2^2 + m_1^2}{2m_2} \right], \tag{12}$$

$$\cos\theta \in [-1, +1] \ . \tag{13}$$

Let us now consider these quantities for $\Delta m \ll m_1$. Working to leading order in $\Delta m$, we find that the maximum value of $E_1$, given in Eq. (12), is

$$\frac{m_2^2 + m_1^2}{2m_2} \approx m_1 \left( 1 + \frac{1}{2} x^2 \right), \tag{14}$$

where

$$x \equiv \frac{\Delta m}{m_1} \ . \tag{15}$$

We can therefore parameterize

$$E_1 = m_1 \left( 1 + \frac{1}{2} a x^2 \right), \tag{16}$$

where $0 \leq a \leq 1$ varies from event to event. Note that the $\mathcal{O}(x)$ piece vanishes. To leading order in the mass splitting, we then find

$$m^2_{\tilde{l}\mu} - M^2 \sim - \left[ (M^2 + m_1^2) + \cos\theta \sqrt{a} (M^2 - m_1^2) \right] x \ . \tag{17}$$

In reality, $E_{\text{shift}}$ is defined by the peak of the $m^2_{\tilde{l}\mu}$ distribution to be

$$E_{\text{shift}} = M - \sqrt{m^2_{\tilde{l}\mu}|_{\text{peak}}} \ , \tag{18}$$

and so it depends on the matrix elements governing the decays. Still, recalling that $a \leq 1$, the second term on the right-hand side of Eq. (17) is always smaller than the first term by at least

$$\frac{M^2 - m_1^2}{M^2 + m_1^2} \ . \tag{19}$$

Thus, a rough estimate for the mass splitting $\Delta m$ can be obtained from

$$E_{\text{shift}} \sim \frac{M^2 + m_1^2}{2 M m_1} \Delta m \ . \tag{20}$$

Since the ratio of Eq. (19) will be measured, we will know the accuracy of this estimate.

**Beyond Leading Order.** In fact, for a scalar $\tilde{l}_2$, we can carry out the analysis exactly (including terms higher order in $\Delta m$), and for all possible matrix elements, since we can determine the $m^2_{\tilde{l}\mu}$ peak position based solely on kinematics.

The crucial point is that, since the sleptons are scalars, the $\tilde{l}_2 \to \tilde{l}_1 X$ decays are uniformly distributed in $\cos\theta$. For a fixed $E_1$, then, these distributions are centered at

$$m^2_{\tilde{l}\mu} = m_1^2 + \frac{M^2 - m_2^2}{m_2} E_1 \ , \tag{21}$$

with width

$$\Delta(m^2_{\tilde{l}\mu}) = 2\frac{M^2 - m_2^2}{m_2}\sqrt{E_1^2 - m_1^2} \ . \tag{22}$$

As $E_1$ decreases from $(m_2^2 + m_1^2)/(2m_2)$ to $m_1$, the width gets smaller and smaller, until the distribution becomes infinitely thin and centered at

$$\widehat{m}^2_{\tilde{l}\mu} = m_1^2 + \frac{M^2 - m_2^2}{m_2} m_1 = M^2 - \frac{M^2 + m_1 m_2}{m_2}\,\Delta m \ . \tag{23}$$

The total distribution is obtained by adding up all the contributions from different values of $E_1$ with the appropriate weights.

We reach the following two conclusions. First, the peak of the total distribution is at $\widehat{m}^2_{\tilde{l}\mu}$. To see this, note that

$$\begin{aligned}\widehat{m}^2_{\tilde{l}\mu} \in \Bigg[ & m_1^2 + \frac{M^2 - m_2^2}{m_2}\left(E_1 - \sqrt{E_1^2 - m_1^2}\right), \\ & m_1^2 + \frac{M^2 - m_2^2}{m_2}\left(E_1 + \sqrt{E_1^2 - m_1^2}\right)\Bigg]\end{aligned} \tag{24}$$

for all possible $E_1$. Thus every $E_1$ contributes to this value of $m^2_{\tilde{l}\mu}$, and this is the only value of $m^2_{\tilde{l}\mu}$ that every $E_1$ contributes to. It is therefore the peak.

Second, since the distribution is not symmetric about the peak, the mean of the distribution need not be at $\widehat{m}^2_{\tilde{l}\mu}$. This is relevant, because it means that the peak after experimental smearing need not be at $\widehat{m}^2_{\tilde{l}\mu}$. However, the mean must satisfy

$$\overline{m}^2_{\tilde{l}\mu} \in \left[\widehat{m}^2_{\tilde{l}\mu}, m_1^2 + \frac{(M^2 - m_2^2)(m_2^2 + m_1^2)}{2m_2^2}\right] . \tag{25}$$

Thus we see that, to first order in $\Delta m/m_2$, the peak and the mean coincide, reproducing the result of Eq. (20).

**The Analysis.** We now illustrate our method by simulating events in a concrete example model. Rather than simulate a realistic supersymmetric model, we use HERWIG [10, 11] to specify a model to isolate the processes we are interested in, namely superpartners produced through $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, and $\tilde{g}\tilde{g}$ pair production, followed by the cascade decays $(\tilde{g} \to)\tilde{q} \to \chi_1^0 \to \tilde{l}_{1,2}$. To do this, we choose $m_{\tilde{g}} = 650$ GeV, all squarks degenerate with $m_{\tilde{q}} = 450$ GeV,

$$\begin{aligned} M = m_{\chi_1^0} &= 225.2 \text{ GeV} \ , \\ m_2 = m_{\tilde{l}_2} &= 139.9 \text{ GeV} \ , \\ m_1 = m_{\tilde{l}_1} &= 134.9 \text{ GeV} \ , \end{aligned} \tag{26}$$

and all other superpartners very heavy, so that they are decoupled from collider events. As mentioned above, it suffices for our purposes to consider flavor-diagonal soft terms and neglect left-right slepton mixing. We then let $\tilde{l}_1 = \tilde{e}_R$ and $\tilde{l}_2 = \tilde{\mu}_R$, and set $B(\chi_1^0 \to \tilde{l}_1) = B(\chi_1^0 \to \tilde{l}_2)$, as appropriate for the case of a gaugino $\chi_1^0$ and right-handed sleptons.

We generate events for a $\sqrt{s} = 14$ GeV LHC and pass these events through a generic LHC detector simulation, ACERDET 1.0 [12]. We configure ACERDET as follows: electrons and muons are selected with $p_T > 6$ GeV and $|\eta| < 2.5$. Electrons and muons are considered to be isolated if they lie at a distance greater than $\Delta R > 0.4$ from other leptons or jets and if less than 10 GeV of energy is deposited in a cone of $\Delta R = 0.2$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The lepton momentum resolutions we use are parameterized from the results of Full Simulation of the ATLAS detector [13]. (Our electrons are smeared according to a pseudo-rapidity-dependent parameterization, whilst muons are smeared according to the results for $|\eta| < 1.1$). ACERDET does not take into account lepton reconstruction efficiencies. We therefore apply by hand a reconstruction efficiency of 90% to the muons and a reconstruction efficiency of 77% to the electrons. This gives 0.86 as the ratio of electron to muon reconstruction efficiency. We generate 20,000 events (before any cuts or requirements are imposed), which corresponds to 40,000 $\chi_1^0$ decays. The supersymmetry cross section for the events of interest and for the parameters we have chosen is $\sim 50$ pb, and so our event samples assume an integrated luminosity of $\mathcal{L} \sim 0.4$ fb$^{-1}$. In a more realistic model, only a fraction $\epsilon$ of all supersymmetry events will satisfy our event criteria, and so the assumed luminosity is 0.4 fb$^{-1}/\epsilon$.

The ATLAS trigger and reconstruction have been modified recently to include the possibility of triggering on and reconstructing meta-stable sleptons [14]. We conservatively restrict ourselves to consideration of sleptons traveling fast enough to arrive in the principal time bin (25 ns wide). Furthermore, as mass resolution degrades as $\beta$ approaches unity, it is necessary to place an upper limit on $\beta$. Combining these two requirements we demand that the $\tilde{l}_1$ candidates have velocity $0.6 < \beta < 0.8$ in agreement with Ref. [15]. Note that the upper cut on $\beta$ will also greatly reduce backgrounds [16]; we assume here that the remaining background events do not impact our results significantly.

For the $\tilde{l}_1$, we take their momenta $|\vec{p}_{\tilde{l}_1}|$ from truth and

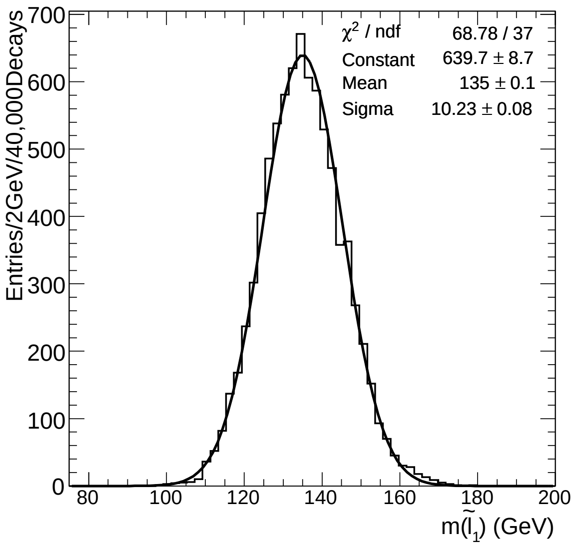


FIG. 1: Reconstructed $\tilde{l}_1$ with $0.6 < \beta < 0.8$ after smearing $\tilde{l}_1$ momenta with a Gaussian with $\sigma = 0.05|\vec{p}_{\tilde{l}_1}|$ centered on the true momentum and after smearing $\beta$ with a Gaussian with $\sigma = 0.02$.

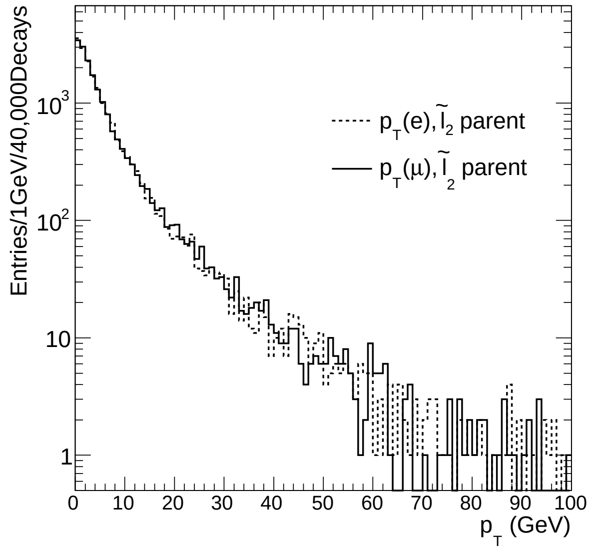


FIG. 2: The $p_T$ distribution of leptons produced by the three-body decays of $\tilde{l}_2$.

smear them by a Gaussian with $\sigma = 0.05|\vec{p}_{\tilde{l}_1}|$. We also smear the $\beta$ by a Gaussian with $\sigma = 0.02$. These choices are again motivated by the results of Ref. [15] and their reconstruction of the $\tilde{l}_1$ by measuring slepton time of flight with the ATLAS RPC chambers. We assume that $m_1$ is well measured, so we scale the four-momentum components to give the exact value of the mass. The resulting $\tilde{l}_1$ mass distribution is given in Fig. 1. We now take our measurement of $m_1$ to be 134.9 GeV. (Although our Gaussian fit actually gives $135.0 \pm 0.1$ GeV, we assume that there is no systematic which would prevent us from obtaining 134.9 GeV exactly.)

To eliminate the soft leptons from $\tilde{l}_2$ decays, we impose a hard $p_T$ cut of 30 GeV. The $p_T$ distribution of these soft leptons is shown in Fig. 2, from which we learn that such a cut is indeed a reasonable choice. Of course, in reality, the information presented in this Figure will not be available, and the experimenters will have to work by trial and error to find an optimal cut that gives the largest number of peak events while maintaining a clean peak.

We first consider all OS $\tilde{l}_1^{\pm} e^{\mp}$ and $\tilde{l}_1^{\pm} \mu^{\mp}$ events and reconstruct the invariant masses $m_{\tilde{l}_1 e}$ and $m_{\tilde{l}_1 \mu}$, imposing the 30 GeV $p_T$ cut on leptons. Based on Eq. (20), we expect $\widehat{m}_{\tilde{l}_1 e} - \widehat{m}_{\tilde{l}_1 \mu} = 5.6$ GeV:

$$\begin{aligned} \widehat{m}_{\tilde{l}_1 e} &= 225.2 \text{ GeV} , \\ \widehat{m}_{\tilde{l}_1 \mu} &= 219.6 \text{ GeV} . \end{aligned} \tag{27}$$

The invariant mass distributions are shown in Figs. 3 and 4. We decompose each of these distributions into two pieces by fitting them to the sum of an exponentially falling contribution and a Gaussian distribution, with form

$$\frac{dN}{dm} = N_{\text{tot}} \left[ (1 - f_{\text{sig}}) |a| e^{am} + f_{\text{sig}} \sqrt{\frac{2}{\pi}} \frac{1}{\sigma} e^{-\frac{(m-\text{mean})^2}{2\sigma^2}} \right] , \tag{28}$$

where $a$ and mean have units of GeV$^{-1}$ and GeV, respectively. These decompositions are also shown in Figs. 3 and 4. The peaks of the Gaussian components then give us

$$\begin{aligned} \widehat{m}_{\tilde{l}e} &= 225.4 \pm 0.1 \text{ GeV} , \\ \widehat{m}_{\tilde{l}\mu} &= 219.2 \pm 0.3 \text{ GeV} . \end{aligned} \tag{29}$$

Thus, the separation between the peaks is experimentally well established. Using Eq. (20), we infer from the results of Eq. (29) that the selectron and the smuon are split in mass, with

$$\Delta m = 5.5 \pm 0.3 \text{ GeV} , \tag{30}$$

to be compared with our input value of 5.0 GeV. The exponentially-falling background in Figs. 3 and 4 is purely combinatoric. It consists of combinations of a $\tilde{l}_1$ with a lepton on the "other side" of the event. In this toy MC we neglected other sources of SUSY background, from events with more than one lepton on each side of the decay. One can check however, (see Ref. [17]) that these hardly affect our results, since the decay chain we considered here is the dominant one.

So far we considered events with OS $\tilde{l}_1$ and lepton. It is also instructive to examine the equivalent SS invariant mass distributions, shown in Figs. 5 and 6. As expected, we see no peak in the $\tilde{l}_1^{\pm} e^{\pm}$ distribution, and only the shifted peak in the $\tilde{l}_1^{\pm} \mu^{\pm}$ distribution. Additionally we see that the muon peaks in the OS and SS samples are of

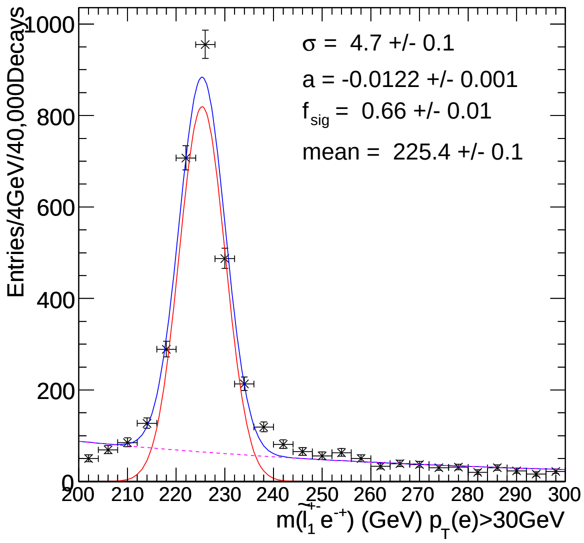


FIG. 3: The $\tilde{l}_1^{\pm} e^{\mp}$ invariant mass distribution. The fit parameters $\sigma$, $a$, $f_{\rm sig}$, and mean are defined in Eq. (28).

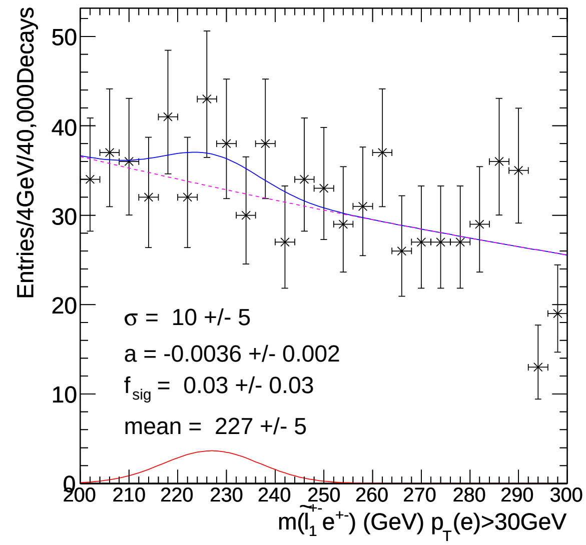


FIG. 5: The $\tilde{l}_1^{\pm} e^{\pm}$ invariant mass distribution. The fit parameters $\sigma$, $a$, $f_{\rm sig}$, and mean are defined in Eq. (28).

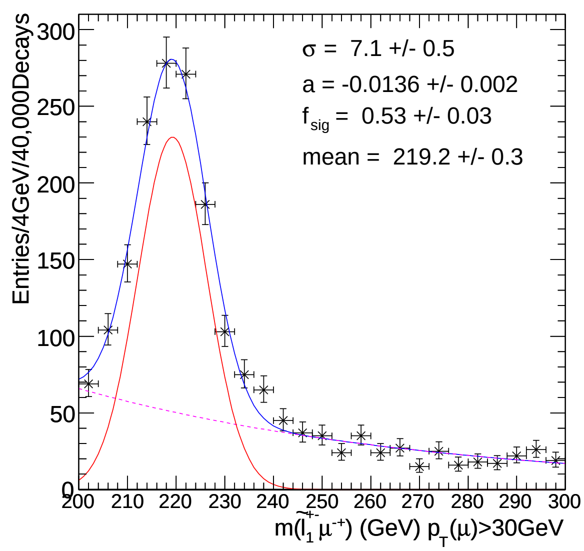


FIG. 4: The $\tilde{l}_1^{\pm} \mu^{\mp}$ invariant mass distribution. The fit parameters $\sigma$, $a$, $f_{\rm sig}$, and mean are defined in Eq. (28).

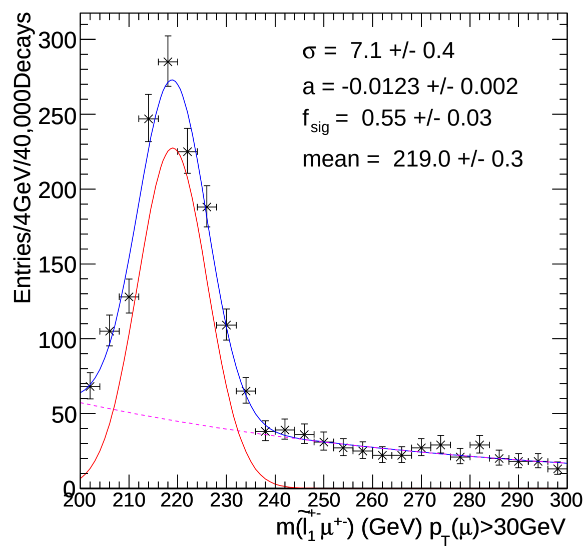


FIG. 6: The $\tilde{l}_1^{\pm} \mu^{\pm}$ invariant mass distribution. The fit parameters $\sigma$, $a$, $f_{\rm sig}$, and mean are defined in Eq. (28).

similar size. This implies that the probability for charge-preserving and charge-flipping decays are similar. This is not a given [8, 9], and so provides an interesting additional constraint on supersymmetric models. Note that, if the light sleptons are mixed flavor states, the SS distribution can serve to reduce some of the background to the shifted peak. With mixed states, Fig. 4 would contain contamination from direct neutralino decays to $\tilde{l}_1$ and a muon, but these must have opposite charges, and so do not contribute to the SS distributions.

It would be nice to close this section by reporting a minimum $\Delta m$ that, given our assumptions about the experiment, could be established and measured. The power to discriminate peaks will depend on many things, however. These include, but are not limited to, the cross section in each peak, the degree to which the peak shapes are modified by variation in acceptance across each plot, the cross section of the underlying backgrounds, and the uncertainties in those backgrounds. As mentioned above, with the strict upper cut on $\beta$ that we used, we do not expect significant SM background. There would be however SUSY background as well as cavern back-splash background (not modeled in this investigation). For the numbers of events simulated in this study, and with not

all sources of backgrounds simulated, it is clear that the errors on the means fitted to the invariant mass peaks, being of order 0.3 GeV, would suggest that peak discrimination at the 5 sigma level is unlikely to be below 1 or 2 GeV. Conversely, one would hope that discrimination at the level of 5 to 10 GeV (the width of the reconstructed invariant mass peaks) ought to be possible, and is indeed demonstrated here.

**Conclusions.** We described a method for determining whether a newly discovered long-lived particle is accompanied by another particle of almost degenerate mass, and for measuring the mass difference between the two.

In the case of supersymmetry, which is the focus of our discussion, such measurements are central to analyzing the flavor structure of the theory, which will tell us about the origin of supersymmetry breaking. If the mechanism that mediates supersymmetry breaking is minimally flavor violating (MFV) [18, 19], such as with pure gauge-mediation, then the mass splitting between the selectron and the smuon is expected to be determined by the muon-Yukawa squared, $\Delta m/m \lesssim y_\mu^2 \sim 10^{-6}\tan^2\beta$, below the percent level. If we can experimentally establish a larger mass splitting, then we would obtain an intriguing clue for contributions that are not MFV [1].

If the dominant mechanism of supersymmetry breaking is gauge-mediation, then the lightest charged slepton can be long-lived and leave a charged track in the muon detector of ATLAS/CMS. If the mass splitting is large enough that the transverse momenta of all the resultant leptonic decay products are frequently above the experimental reconstruction minimum (likely to be in the range 5 to 10 GeV) then we can fully reconstruct the $\tilde{l}_2 \to \tilde{l}_1$ decays and measure the mass splitting directly. If, however, the mass splitting is only a few GeV, the leptons produced in this decay are typically too soft to be detected. Despite this, as we have shown here, the $\tilde{l}_1 l$ invariant mass distribution will exhibit a double peak structure. The separation between the two peaks can be experimentally established and measured, and its value can be translated into a value of the slepton mass splitting.

We note that a related study was presented in Ref. [20] in the context of gravity-mediated supersymmetry breaking, with a neutralino lightest supersymmetric particle. The events are characterized by missing energy, and the measurement of the slepton mass splitting is based on the kinematic edges of the $m^2_{l^+l^-}$ distribution from $\chi_2^0 \to \tilde{l}^\pm_{1,2}\ell^\mp \to \chi_1^0 \ell^\mp \ell^\pm$.

With non-MFV supersymmetry breaking, we expect that the slepton mass eigenstates are not identical to the lepton flavor eigenstates. In this case, the decays we have considered contain a great deal of flavor mixing information [9, 21, 22], and our method can be used to measure not only the mass splitting, but also the mixing [17]. The SS sample will be particularly useful in this case, as it is only sensitive to neutralino decays to $\tilde{l}_2$, and therefore only exhibits the "shifted peak." Counting the number of electrons and muons in this shifted peak gives a clean measurement of the flavor decomposition of $\tilde{l}_2$.

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